The Mu2e Experiment at Fermilab

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Abstract. The Mu2e collaboration has proposed an experiment to search for the coherent decay of a muon to an electron in the Coulomb field of a nucleus with an expected sensitivity of $R_{\mu e} < 6.0 \times 10^{-17}$, at the 90% confidence level. Mu2e has received strong support from the P5 panel and has received Stage I approval from Fermilab. If all resources are made available as required, the experiment could begin taking data as early as 2016.

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INTRODUCTION

In the process of muon to electron conversion the initial state is a muonic atom and the final state consists of a mono-energetic electron recoiling against an intact atomic nucleus. There are no neutrinos in the final state. The recoiling nucleus is not observed, leaving an observed final state of just the electron, which has an energy of the muon rest mass less corrections for the nuclear recoil and the K-shell binding energy of the muon.

The result of the experiment will be expressed by the ratio,

$$R_{\mu e} = \frac{\Gamma(\mu^- N(A,Z) \to e^- N(A,Z)}{\Gamma(\mu^- N(A,Z) \to \nu_\mu N(A,Z-1)}, \tag{1}$$

where $N(A,Z)$ denotes a nucleus with mass number A and atomic number Z. The numerator is the rate for the conversion process and the denominator is the rate for muon capture on the same nucleus.

In the standard model, including non-zero neutrino masses, $R_{\mu e}$ is non-zero but is much smaller than the reach of present or imagined experiments. This leaves a large window of opportunity for the observation of physics beyond the standard model and most new physics scenarios predict that this process will occur at some level. In particular, scenarios that predict that SUSY is within the reach of the LHC also predict $R_{\mu e} \approx 10^{-15}$, a rate for which Mu2e expects observe, after 2 years of running, about 40 events on a background of fewer than 0.5 events.

The process of muon to electron conversion is just one example in the broader field of Charged Lepton Flavor Violation (CLFV). An excellent review of CLFV and the flavor physics of leptons can be found in reference [1]. Two classes of diagrams can contribute to conversion. The first class includes magnetic moment loop diagrams with a photon exchanged between the loop and the nucleus; these diagrams can proceed with many different sorts of particles in the loop, including, but not limited to, SUSY particles, heavy neutrinos and a second Higgs Doublet. This class of diagrams also produces non-zero rates for the process $\mu \to e\gamma$. The second class includes both contact terms that parameterize compositeness and the exchange of a new heavy particle, perhaps a Leptoquark or a Z'. This class of diagrams does not give rise to the process $\mu \rightarrow e\gamma$. The bottom line is that, through these processes, Mu2e has sensitivity to mass scales up to about 10,000 TeV, far beyond the scales that will be accessible to direct observation at the LHC.

THE EXPERIMENTAL TECHNIQUE

The Mu2e apparatus is described in detail in the Mu2e proposal [2]. The basic idea behind Mu2e is motivated by the MECO [3] experiment, which, in turn, was motivated by the MELC experiment. A beam of low momentum negative muons is stopped on a set of thin Al target foils and the muons drop to the K-shell, forming a muonic atom. The Bohr radius of the K-shell of muonic Al is about 20 fm and nuclear radius of Al is about 4 fm, which yields a large overlap between the muon wavefunction and that of the nucleus. The two major decay modes of muonic Al are muon decay in orbit (DIO), which occurs about 40% of the time, and muon capture on the nucleus, which occurs about 60% of the time. DIO produces electrons with a continuous energy spectrum, which is roughly like a Michel spectrum, smeared out but the orbital motion of the muon and with a long radiative tail that extends almost to the muon mass. In one extreme configuration, both neutrinos are at rest and the electron recoils against the intact Al nucleus. This is the configuration in which the electron has the maximum energy in the lab frame, about 105 MeV for muonic Al. The energy spectrum falls to this end point roughly as $(E - E_{\mathrm{max}})^5$. Muon capture produces, protons, neutrons and photons; these produce singles rates in the detector but produce reconstructible electrons only via secondary processes.

The μ to e conversion produces a mono-energetic electron with an energy, ignoring neutrino masses, equal to that of the endpoint of the continuous spectrum from DIO. In summary, the technique is to carefully measure the energy spectrum from electrons emitted from the target foils and to search for an excess at the endpoint.

The muon beam used by Mu2e is produced using 8 GeV protons from the Fermilab accelerator complex. In order to minimize construction costs, Mu2e will reuse many parts of the accelerator complex following the completion of Tevatron Run II. A bunch of protons with a full width of about 100 ns is steered onto a pencil shaped Au target located in the middle of a high field graded-field solenoid, the Production Solenoid (PS), shown in Figure 1. In the production target, p-Au interactions produce pions that are captured into helical trajectories in the field of the solenoid; these pions decay into muons that are also captured by the field of the solenoid. Mu2e is interested in the backscattered muon beam. The PS has a graded magnetic field, with a field of 5 T at the proton-downstream end, falling to about 2.2 T at the proton-upstream end. This forms a magnetic mirror and reflects a portion of the forward going pions and muons, thereby increasing the yield of captured muons.

The backward going muons exit the PS and enter the S-bend graded field Transport Solenoid (TS), also shown in Figure 1. The bend in the TS induces a dipole term which allows, by appropriate placement of absorbers and collimators, the sign selection of the muon beam and the stopping of any anti-protons accompanying the muon beam. The

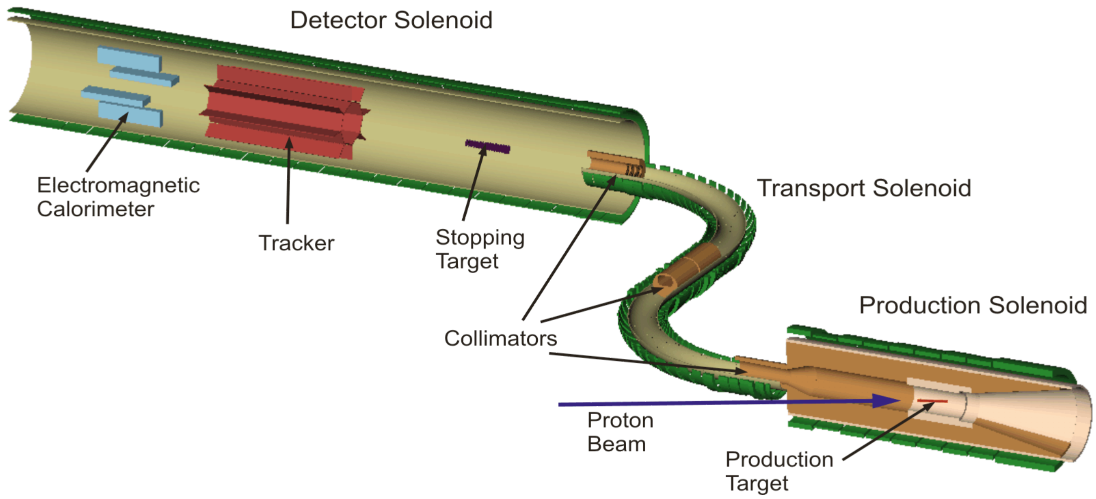

FIGURE 1. Diagram of the Mu2e muon beam-line and detector. The proton beam enters from the left. A back-scattered muon beam is captured by the Production Solenoid and transported through the S-bend Transport Solenoid to the stopping targets. Conversion electrons, produced in the stopping target are captured by the magnetic field in the Detector Solenoid and transported through the Tracker, which makes a precision measurement of the momentum. The conversion electrons then strike the Electromagnetic Calorimeter, which produces an event trigger.

TS transmits the μ^- beam into the Detector Solenoid (DS) where it encounters the foils that comprise the stopping target. Downstream of the target is a tracking system and downstream of that is an electromagnetic calorimeter (ECal). In both of these devices, the inner region, to a radius of about 38 cm is empty. This allows those muons that do not stop in the stopping target to pass through the detector to a beam dump.

The DS magnetic field is also graded to form a magnetic mirror that reflects some backwards going electrons towards the tracker. In the volume occupied by the tracker and ECal, the DS magnetic field is highly uniform at 1.0 T. When a conversion or DIO electron is emitted from the stopping target, it travels in a helical trajectory and, if it has sufficient transverse momentum, p_T, its trajectory will be measured by the tracker. Only those electrons with $p_T > 55$ MeV$/c$ will reach the tracker and only those with $p_T > 90$ MeV$/c$ will intersect enough of the tracker to form a reconstructible track. Because almost all tracks from DIO have $p_T < m_\mu/2$ they will never reach the tracker. This is the key to making a measurement of $R_{\mu e}$ with a sensitivity of $O(10^{-17})$: the apparatus is only sensitive to the tail of the DIO energy distribution. Electrons that pass through the tracker will eventually intersect the ECal, where they will provide an event trigger plus an energy measurement and a position measurement, both of which can be used to confirm track candidates.

The μ^- beam that reaches the stopping target is contaminated by many e^- and some π^-, both of which can produce false signals when they interact with the stopping targets. These backgrounds occur promptly. To defeat them, the experiment exploits the lifetime of muonic Al, about 864 ns: Mu2e waits for 700 ns following the arrival of the proton bunch at the production target and then begins counting electrons that are emitted from the foils of the stopping target. By this time, all of the beam from the production target has passed through the stopping target and the prompt backgrounds have died away. After a total of 1694 ns the cycle is repeated.

It is also critical that few protons arrive at the production target between the bunches. If protons arrive out of time, they can produce e^- and π^- that arrive at the stopping target within the live gate. To reduce this background Mu2e requires an extinction of 10^{-9}; that is, for every proton that arrives at the production target within the bunch, there should be no more than 10^{-9} protons between bunches.

The dominant background sources are expected to be poorly measured DIO electrons (0.225 events), radiative π^- capture on the target foils (0.063‡), scattered beam electrons (0.036‡), μ decay in flight (0.036 ‡), cosmic ray induced (0.016), and six other processes (0.039) for a total estimated background of 0.415 events. These numbers are quoted for a nominal 2 year run. The processes marked ‡ scale with extinction and are reported for an extinction of 10^{-9}.

The critical path for the Mu2e apparatus is the design and construction of the solenoid system. If all resources are made available as required, the solenoids could be installed by 2016. The collaboration has estimated a Total Project Cost on the order of M$200.

Summary and Conclusions

The goal of the Mu2e experiment is to observe μ to e conversion or to set an upper limit of $R_{\mu e} < 6 \times 10^{-17}$ at the 90% CL and to do so in two years of running. This is 10,000 times better than the previous best limit [4] and mass scales up to O(10,000 TeV) are within reach. For $R_{\mu e} = 10^{-15}$ the detector would see about 40 events on a background of less than 0.5 events. The experiment has been strongly endorsed by the P5 committee and has received Stage I approval from Fermilab. Visit the Mu2e home page [5] to keep up to date with the experiment.

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